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RADIOISOTOPE PRODUCTION IN AIR AND SOIL IN RHIC

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I. Introduction

This note is concerned with estimating the annual radioisotope production in air and soil in the Relativistic Heavy Ion Collider. Such estimates are needed as part of the evaluation of the effects of RHIC on the environment. Slightly activated air interior to the collider will be exhausted and eventually migrate, in much diluted concentrations, to the site boundary. Similarly, isotopes produced in soil are leached out by rainwater and again, in diluted form, eventually reach the site boundary. A study of migration, decay, and dilution processes is not considered here; rather the estimates of isotope production serve as "source" input for such a study.

II. Beam Loss in RHIC

A discussion of beam loss in RHIC is given in Appendix A, to which the reader is referred. This section presents an abbreviated summary of beam loss, and addresses one mode of operation not considered in Appendix A.

A conservative estimate of the total accelerated ions per year, expressed in equivalent Au ions at full RHIC energy (100 GeV/A), is 8.577×10^{14} . These ions interact in 4 classes of locations: (1) beam dumps, (2) limiting aperture collimators (LAC's), (3) the experimental interacting regions (IR's), and (4) "anywhere else". The distribution of "loss" among these 4 locations, expressed in percent, is expected to be: dumps: 88.76, LAC's: 9.49, IR's: 0.40, and "other points": 1.35.

Two additional aspects of the discussion in Appendix A should be repeated here for emphasis. The first is that an "upgraded" RHIC, i.e., a RHIC with 4 times the intensity given in the design proposal¹ has been assumed. Secondly, it should be noted that superconducting colliders are inherently clean because of the sensitivity of magnet coils to radiation heating. The LAC's, for example, exist to protect the coils of the magnets; if they do not work well, the collider cannot run at the design energy and intensity.

One mode of running not explicitly considered in Appendix A is fixed target operation. The scenario for this operation is described by Young². The important point here is that long running times are also a "given" in this mode: Reference 2 assumes 12 hour runs and derives properties of the gas jet and foil targets to accommodate the running time criteria. Thus, the net

effect of trading colliding beam running for fixed target running would be to DECREASE the total interactions by a factor of 2, there being only one beam.

III. Method of Calculation/CASIM Modification

The basic method of calculation proceeds in 3 steps. First a "reasonable" approximation of the geometry of the loss points is made, as discussed in the next section of this note. Then the hadron cascade Monte Carlo computer code CASIM^{3,4} is used to calculate the total number of interactions (stars) in air or soil per interacting ion. Finally, estimates are made for the radioisotope production per star (sections VI and VII below).

CASIM has been used for shielding calculations at FNAL and the AGS, and CASIM results form the basis for SSC shielding criteria⁵. To simulate heavy ion interactions, a modest change was made to the code which the remainder of this section describes.

The standard CASIM computer code allows only protons, neutrons, and pions as incident (primary) hadrons. As discussed in Ref. 2, CASIM propagates only 1 particle from each interaction in a hadronic cascade, with that particle being assigned a weight to represent the entire multiplicity of particles emerging from each interaction. The weight of each primary is 1. CASIM was modified to allow heavy ions as primaries. Energy deposition from the primary is calculated assuming the incident is a proton with weight Z^2 . The ion is assigned an interaction cross section according to the Bradt-Peters formula⁶

$$\sigma = 68.8 \text{ mb } (A^{1/3} + B^{1/3} - 1.32)^2$$

where A is the atomic weight of the ion and B is the atomic weight of the medium (CASIM allows 5 mediums in a given calculation). When the ion interacts it is turned into either a proton or neutron (selected by the Z/A ratio) and given weight A.

The deficiency of this approximation is that ion fragments are not considered as interaction products. Each collision is therefore more "central" than in reality which tends to overestimate transverse energy and multiplicity. However, this approximation does accurately take into account the "first-order" differences between nucleons and heavy ions and heavy ion data taken to date at both the AGS and CERN indicate that collisions are more central than a simple geometrical model would indicate⁷.

IV. Approximation of Loss Point Geometries

The approximation of a RHIC magnet cross-section is shown in Fig. 1. The cryostat volume is, in fact, quite complicated as shown in Fig. IV-26 of Ref. 1. In the calculations reported here, this volume is treated as Fe with a density of 0.15 g/cm^3 . Vacuum exists for $R < 3.65 \text{ cm.}$, and the coil, yoke regions (called "YOKE" in Fig. 1) is assumed to be normal Fe with density 7.8 g/cm^3 . The fact that the coil, yoke regions are taken as centered in the cryostat is another simplification made for convenience.

Neither the dump nor LAC's are yet designed, so some "ball park" approximations are required. The current proposal calls for an internal dump immediately upstream of the insertion magnet Q4. The dump material is taken as Fe. The dump length is taken as 2 meters (over 12 proton interaction lengths) and the radial extent was determined by requiring that less than 2% of the energy escape laterally from a solid block of material. This thickness is 45 cm. It should be noted that the real dump will no doubt be composed of different material(s), but a generic feature of dumps is that only a few percent of the energy be allowed to escape the core. The lattice approximation as a function of z (distance along the beam) is shown in Fig. 2. The magnet nomenclature is as in Table IV-5 of Ref. 1. (The marble shown in this figure is discussed in the next section). It is assumed that the dump itself protrudes 2 cm into the vacuum pipe in the vertical rectangular coordinate. This is indicated by the dump "lip" in Fig. 2. Some upstream kickers must deflect the beam on this lip when triggered. The dump region is located in the "expanded tunnel section" which has a radius of 3.05 meters and a floor 2.1 meters below beam center. No account is taken of the other arc which is actually present in the tunnel.

The LAC region is approximated also by the geometry shown in Fig. 2, except that the thickness of the collimator is taken to be 10 cm instead of 45 cm used for the dump.

For ions which interact "anywhere else" (see section II), we assume interaction near the maximum beta location. The geometry is shown in Fig. 3. No shielding is present in this geometry.

The "geometry" at the intersection regions is difficult to approximate. In general, large detectors will be present which represents, for the concerns here, a large amount of shielding. No attempt has been made to simulate this situation; instead, a safe "overestimate" has been made as discussed in the next section.

V. CASIM Results

A. Beam Dump

Surrounding the "core" of the beam dump, it is necessary to provide some amount of shielding material to protect maintenance personnel and others requiring access during "collider-off" periods from induced activity in the dump core. Marble (CaCO_3 with density 2.7 g/cm^3) turns out to be a good choice for such a material, since the activity induced in marble is small in comparison with the dense, high-Z materials typically used in the outer regions of beam dumps.

Figure 4 shows the CASIM stars in air per interacting Au ion as a function of marble thickness. Also shown in this figure is the dose equivalent per beam dump (per 2.5×10^{11} 100 GeV/A gold ions) at the top of the berm over the expanded tunnel section which is 13 feet thick. Figure 5 shows stars in soil as a function of depth assuming a conservative 10 cm of marble shield.

The statistical errors in the total number of stars in these calculations, and those below, are typically 15%.

B. LAC

We have assumed here also that 10 cm of marble exists. The total stars in air are 61 per Au ion (in contrast with 19.1 per ion in the dump geometry) and 4416 stars in soil per Au ion (in contrast with 1693 stars per ion in the dump geometry).

C. Loss at High Beta Point

Two cases were considered: the beam scraping the beam pipe at the downstream end of Q1 and at the downstream end of Q2. The Q2 case turned out to be the worst, with 160 stars in air per ion and 11,650 stars in soil per ion. (Q1 scraping is worse as concerns maximum dose equivalent at the top of the berm. Loss of the entire beam here is a good approximation of the "worst case accident" scenario. It results in 90 mRem at the berm top).

D. Loss at the IR Region

As mentioned in the preceding section, the geometry depends on the experimental apparatus. A conservative upper limit should be obtained by using the LAC results with 3 modifications. The first modification is to multiply the results by 2 to account for the energy, if not the detailed

dynamics, in beam-beam collisions. The second modification is to multiply the stars in air by the ratio of the cross-sectional area of the hall to that of the expanded tunnel section. This ratio, for the facility hall (taken as "typical") is ~ 5.4 . The third change has to do with a breakdown of the assumption that gold on gold is representative of the worst case. Running periods with lower Z nuclei will be longer and have less loss due to Coulomb processes in the IR regions. However, the ratio of losses at the IR to losses on the LAC will increase. Since we are assuming a greater volume of air in the IR regions, this results in more air isotopes per unit time. For conservatism, we neglect the effect of the longer running times and multiply the losses here by another factor of 2.

E. Summary of CASIM Results

Folding the results given above with the beam loss estimates in section II (Appendix A) gives an estimate of the total number of interactions in air and soil per year. This is shown in Table I. The remaining task is to estimate the radionuclide production per interaction.

Table I. Interaction Per Year in Air and Soil

Loss Point	Stars in Air ($\times 10^{16}$)	Stars in Soil ($\times 10^{18}$)
Dump	1.45	1.29
LAC	0.50	0.36
Other Points	0.19	0.14
I.R.	< 0.45	< 0.06
Total	2.59	1.85

VI. Radionuclides in Air

We have taken the composition of air to be: N_2 (78.08%), O_2 (20.95%), CO_2 (0.03%), A(0.93%) and have ignored trace (order of parts per million) elements. The fraction of interactions for the elemental species given an interaction in air is proportional to the number of atoms of each species present per unit volume and is the following: N(0.784), O(0.211), A(0.005), C(0.00015).

Radionuclide production cross sections are taken from the air activation study at CERN⁸ and are shown in Table II. All except one of these nuclides (⁴¹A) are produced by spallation interactions which are precisely the interactions simulated by CASIM. The prescription for their production is straightforward: the total number of interactions (Table I) is multiplied by the probability that the interaction was with the parent (the fractions given at the end of the preceding paragraph), then by the production cross section for the isotope in question (Table II) and finally divided by the total CASIM air cross section (280 mb). In case the isotope in question comes from more than one parent (e.g., Tritium), a sum over parents is made.

Argon 41, produced copiously by thermal neutrons as shown in Table II, is estimated by a less straightforward procedure. For this isotope we first assume that the hadron flux is in equilibrium everywhere in the RHIC tunnel. The meaning of this statement is that the total neutron flux present in the tunnel air is assumed to be the same that exists in matter after deep penetration. A second assumption is that the thermal cross section (which actually falls inversely with velocity) is constant (610 mb) to 1 eV and zero above this energy. With these assumptions, Figs. VI.12 and VI.13 of Ref. 3 can be used to deduce that the ratio of thermal neutrons to hadrons considered by CASIM (> 750 MeV) is 0.5. A prescription similar to that described above for the spallation products can then be followed. This method of estimation has been shown previously to be in reasonable agreement with measurements⁹.

Table III shows the isotopes of each type per CASIM star and the total isotopes produced per year.

Table II. Radionuclides Produced in Air (from Ref. 8)

Parent	Isotope	Half-Life	Cross Section (mb)
N	^{13}N	10 m	10
	^{11}C	20.4 m	10
	^7Be	53.6 d	10
	^3H	12.2 y	30
O	^{15}O	2.1 m	40
	^{14}O	74 s	1
	^{13}N		9
	^{11}C		5
	^7Be		5
	^3H		30
A	^{41}A	1.8 h	610 (thermal)
	^{35}S	87 d	23
	^{32}P	14.3 d	25
	^{28}Al	2.3 h	13
	^{22}Na	2.6 y	10
C	^{11}C		30
	^7Be		10
	^3H		10

VII. Radioisotopes in Soil

It is well known that the troublesome isotopes produced in soil are ^{22}Na and ^3H . We take production values from FNAL work¹⁰ which are:

^3H 0.075 atoms/star

^{22}Na 0.02 atoms/star

Combining these numbers with the total star estimate in Table I gives:

^3H 1.4×10^{17} atoms/year

^{22}Na 0.37×10^{17} atoms/year

Table III. Radioisotopes Produced in Air

Isotope	Per Interaction	Per Year ($\times 10^{15}$)
^{41}A	.0054	.14
^{35}S	.0004	.010
^{32}P	.0005	.013
^{28}Al	.0002	.005
^{22}Na	.0002	.005
^{15}O	.030	.76
^{14}O	.0008	.021
^{13}N	.035	.91
^{11}C	.032	.83
^7Be	.032	.83
^3H	.107	2.77

VIII. Conclusions

As stated in the introduction, the estimates made here serve only as source terms for an environmental analysis. The numbers here are about 1 order of magnitude less than recent estimates made for the AGS Booster^{9,11}, verifying the intrinsic "cleanliness" of superconducting colliders.

References

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RHIC BEAM LOSS - OVERVIEW

I. Operating Scenario

1. Calculations (at least as concerns radiation) will be made assuming an "upgraded" RHIC. The stored beam will be 4 times the values given in the 1986 reference design ($\times 2$ intensity per bunch and $\times 2$ number of bunches).
2. The operating year is assumed to consist of 34 weeks of physics operations" and 4 weeks of "studies". We assume the average physics run will consist of cycles composed of a set-up fill of 1 hour followed by a physics run of 10 hours. The average "study" will be assumed to be 1 hour.

The total fills per year are then 1038 for operations and 672 for studies.

II. Loss Points

We assume the presence of at least one horizontal and one vertical limiting aperture collimator (LAC). Beam loss will occur at the following points: (1) injection septum, (2) LAC's, (3) beam intersection points, (4) beam dump, and (5) "other points". The catch-all "other points" incorporates losses corresponding to (a) beam-gas interactions, (b) particles which out-scatter from the LAC's (LAC inefficiency), and (conceivably) (c) rapid accidental beam loss. In practice, the most likely "other points" are β (max) locations. If an external dump is required, the ejection septum would be another source of loss, but this possibility is ignored in the remainder of this note.

III. Loss Assumptions

It is a fact that superconducting accelerators are most unforgiving of sloppy beam handling. FNAL has established a fast-loss quench threshold of 1 mJ/g at 80% of quench current. If the vast majority of beam energy does not end up in the (presumably well-shielded) LAC's or beam dump, the accelerator will not "work", i.e., the beam loss will limit the injected intensities to values much lower than the design numbers. For this reason, the commissioning period is not regarded as a problem; although loss will be frequent, the injected intensity will be low, growing to the design intensity only as progress is made on the 'learning curve' of clean beam handling.

The RHIC design proposal contains detailed calculations of many loss mechanisms. The loss in all cases depends on energy and species. Tentatively, the extreme assumption will be made that the collider is always operating with Au on Au at full energy. Given this extreme assumption, the calculations in the RHIC proposal will be taken as valid in the spirit that it would be inappropriate to pile factors of conservatism on top of one another. Loss assumptions are then the following:

1. Injection Septum

We assume 1/2% loss here. It remains to be shown that such a loss will not quench magnets, but that detail is not a concern at the present time. Since this loss is at low (AGS) energy, the consequences are negligible from a radiation hazard point of view.

2. Acceleration

We take no loss here which is compatible with current thinking (S.Y. Lee, private communication). A modest loss assumption would be irrelevant in comparison with the large losses below. The total Au ions at full energy (100 GeV/nucleon) per year is then

$$2 \times 114 \times 2.2 \times 10^9 \times [1038 + 672] = 8.577 \times 10^{14}$$

3. Aperture, RF Losses

Table IV-8 of the RHIC Conceptual Design gives 3% loss for 10 hours. The assumption in this note is that we are concerned with 1 hour set-up cycles, 10 hour physics cycles, and 1 hour study cycles. A priori, one expects the physics runs to correspond to the calculated loss rate, the set-up cycles to have a somewhat higher loss rate, and the studies cycles to be "sloppier" still. Somewhat arbitrarily, we assign a 50% higher (than calculated) loss rate to set-up cycles and 100% (factor of 2) higher loss rate to studies. Assuming a linear time dependence, this loss per fill is then 0.45% for set-up, 0.6% for studies, and 3% for physics.

Ideally, 100% of this loss would occur on the LAC's. We will assume, in this loss and those below, that the LAC's are 90% efficient, i.e., that 10% of the losses that are "supposed" to occur on an LAC in fact occurs on (some number of) "other points".

4. Beam-Beam, Beam-Gas Effects

Calculations of these losses are given in Table IV-14 of the RHIC Conceptual Design and the formula on page 135. For Au, the predominant losses are due to Coulomb effects, which again should end up on the LAC's; the ratio of Coulomb loss/Intersection Region Loss/Beam-Gas is 0.93/0.04/0.03. For these losses, the conservative assumption is that they also apply to set-up and studies fills. Using the aforementioned formula, the total loss in 10 hours is 23%, and in 1 hour is 4.6%.

5. Summary

With the assumptions given above, the total loss per year as a function of location (ignoring the low energy injection loss) is the following:

<u>Location</u>	<u>Au Ions/year</u> ($\times 10^{14}$)
Dump	7.613
LAC's	0.814
Other Points	0.116
I.R	<u>0.034</u>
	8.577

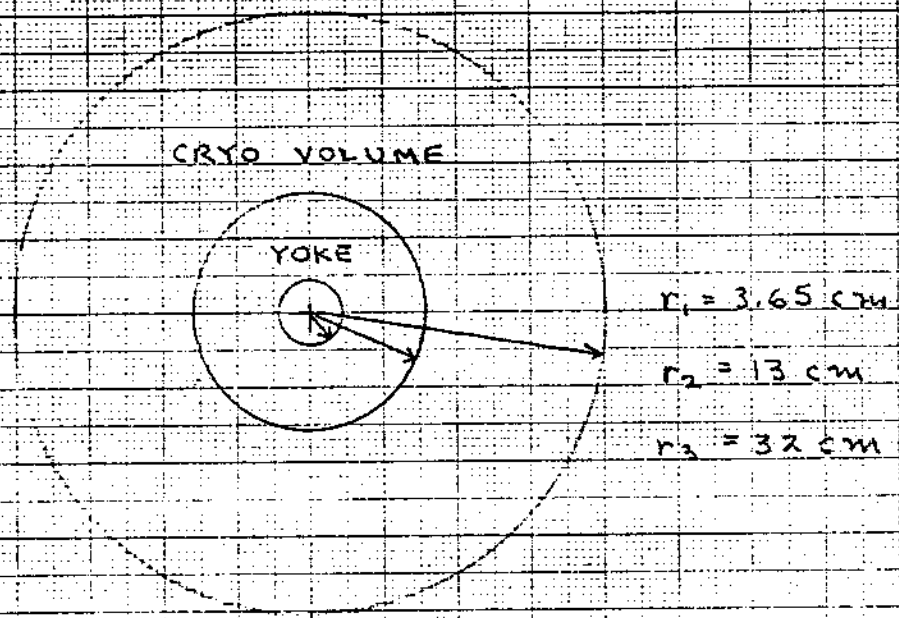
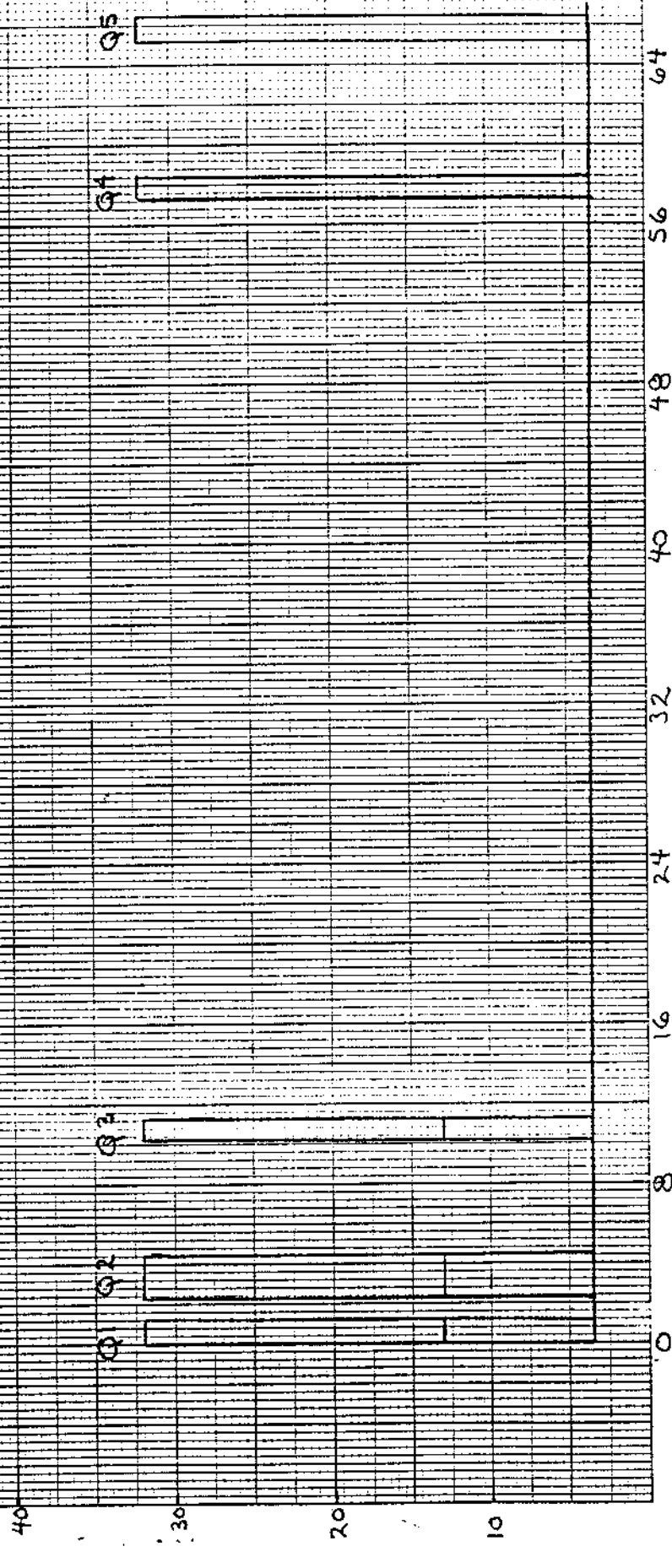


Fig. 1. APPROXIMATION OF RHIC MAGNET CROSS-SECTION

(m) Z

Fig. 3
REPRESENTATION OF POINT LOSS REGION





cm. of marble

